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The Space Density of low redshift AGN

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ABSTRACT

We present a new determination of the optical luminosity function (OLF) of active galactic nuclei (AGN) at low redshifts ($z < 0.15$) based on Hubble Space Telescope (HST) observations of X-ray-selected AGN. The HST observations have allowed us to derive a true nuclear luminosity function for these AGN. The resulting OLF illustrates a two-power-law form similar to that derived for QSOs at higher redshifts. At bright magnitudes, $M_B < -20$, the OLF derived here exhibits good agreement with that derived from the Hamburg/ESO QSO survey. However, the single power law form for the OLF derived from the Hamburg/ESO survey is strongly ruled out by our data at $M_B > -20$. Although the estimate of the OLF is best-fit by a power law slope at $M_B < -20.5$ that is flatter than the slope of the OLF derived at $z > 0.35$, the binned estimate of the low redshift OLF is still consistent with an extrapolation of the $z > 0.35$ OLF based on pure luminosity evolution.

1 INTRODUCTION

The QSO optical luminosity function (OLF) and its evolution with redshift has been studied extensively for over three decades (see e.g. Schmidt 1968, Marshall et al. 1983, Boyle et al. 1988, Hewett, Foltz & Chaffee 1993, La Franca & Cristiani 1997). This has led to a detailed picture of the QSO OLF over a wide range in redshift from $z \sim 0.3$ to $z > 4$. In contrast, the local ($z < 0.15$) QSO OLF is actually much more poorly determined, frustrating attempts to link QSO evolution at moderate to high redshifts with nuclear activity in galaxies at the present epoch.

This is due to a number of factors associated with the compilation of a suitable sample of local active galactic nuclei (AGN) with which to derive the local OLF. First, local AGN are relatively rare. Their space density is approximately 100 times less than that of normal galaxies, and large area surveys are required to yield a statistically useful sample. Secondly, many selection techniques for local AGN suffer from morphological biases. While surveys for stellar-like objects are clearly biased against resolved AGN, galaxy-based surveys are equally biased against objects with a dominant nuclear component. Finally, accurate knowledge of the nuclear OLF requires accurate subtraction of the light from the host galaxy. In the low luminosity AGN ($M_B > -23$) that constitute the vast majority of the low redshift population, the light from the host galaxy may dominate the nuclear luminosity. Even at relatively low redshifts ($z \simeq 0.1$), seeing limitations imposed by ground based observations limit accurate modelling of the luminosity profiles of the central regions of AGN host galaxies to scales typically larger than $1h_{50}^{-1}$kpc.

A recent attempt to estimate the local AGN OLF has been carried out by Köhler et al. (1997), hereinafter K97. Using a sample of 27 candidates selected from the Hamburg/ESO objective prism survey, K97 derived a local AGN LF that exhibited a featureless power law form over a wide range in absolute magnitudes $-24 < M_B < -18$. The form of the low redshift AGN LF is thus very different from the two-power-law luminosity function at higher redshifts ($z \geq 0.5$). This is a significant challenge for any theoretical model which seeks to connect the evolution of QSOs at high redshift with the local AGN population.

The Hamburg/ESO survey covers an extensive area (611deg^2; now extended to 3700deg^2, see Wisotzki 2000) and is free of morphological bias. Unfortunately the spatial resolution (1–2 arcsec) of the survey is not sufficiently good to permit an accurate deconvolution of the galaxy and nuclear light even for the lowest redshift AGN ($z < 0.1$) in the sample. For the $0.07 < z < 0.3$ sample K97 used small-aperture, zero-point corrected B band CCD magnitudes which were subsequently corrected to reflect nuclear luminosities by subtracting a template host galaxy value of $M_B = -21$; for the AGN with $z < 0.07$ corrections were calculated individually and ranged from 0.21 to 1.61 mag.

Until recently, AGN data sets studied with HST were either too small or the samples on which they were based were too heterogeneous to construct a reliable estimate of the local OLF. We report here on the estimate of the local nuclear OLF based on HST observations of 76 AGN selected from a unbiased sample of X-ray selected AGN. The sample is part of the extensive Einstein Medium Sensitivity Survey (EMSS, Stocke et al. 1991) which covers over 400deg^2 and has near-complete (> 96 per cent) optical spectroscopic identification with no morphological bias. An earlier attempt to derive the low redshift OLF using the EMSS was made by della Ceca et al. (1996). They used 226 broad line AGN with $z < 0.3$ to obtain a total (nuclear + host) OLF. This OLF was then convolved with the observed distribution of nuclear-to-total flux ratios for Seyfert 1 and 1.5 galaxies to yield a nuclear OLF. In this paper we propose to improve significantly on this work by using the HST observtions to correct explicity for the host galaxy light in each AGN. In section 2 we report on the measurement of the OLF from this sample, and in sections 3 and 4 we present and discuss the results obtained, comparing them to the K97 results. We present our conclusions in section 5.

2 ANALYSIS

2.1 The data

Details of the comprehensive HST imaging survey from which the sample of AGN used in this analysis were drawn is presented in a paper by Schade et al. (2000, hereinafter SBL). A full discussion of the methods used to select and observe these AGN is presented by SBL, thus only a brief description will be given here.

HST observations of 76 $z < 0.15$ AGN selected from the EMSS survey were carried out in the F814W (I) band, chosen to assist in the detection of the redder host galaxy components over the bluer nucleus. These data were complemented by deeper ground-based observations in the B and R bands for 69 AGN in the survey. A simultaneous three-component parametric model fit to the B, R and I images was performed for each AGN in the sample to derive magnitudes for the nuclear point source, bulge and disk components in each object. Despite the improved spatial resolution afforded with the HST, the fitting procedure is complex and error estimation required significant modelling of the fitting process. For host-dominated objects uncertainties in M_B(host)* were typically ±0.25 magnitudes in the region of the M_B, z plane where the AGN are found, but increased to ±0.5 mag where the nucleus was dominant. Similarly, errors in nuclear magnitudes were ±0.25 mag for bright nuclei but as much as ±0.5 mag for host-dominated objects.

In total, nuclear M_B magnitudes were obtained for 66 AGN in the sample (10 had no detectable nuclear component), and these data form the basis for the calculation of the OLF below. Nuclear absolute magnitudes were found to lie in the range $-14.6 > M_B > -24.1$. The region of the AGN M_B(nuc)$, z$ plane sampled in this study is shown in Fig. 1.

Since we are attempting to contruct an OLF from an X-ray-selected sample we need to ensure that there is a good correlation between nuclear optical and X-ray luminosity for objects in the SBL sample. We used the monochromatic 2 keV X-ray luminosity, $L_{2\mathrm{keV}}$(nuc) and 2500Å UV fluxes,

* In the SBL study all magnitudes were based on the AB system. Nuclear B(AB) magnitudes were derived by applying a mean $(B-I)_{(\mathrm{AB})} = 0.2$ colour correction to the nuclear I(AB)-band magnitudes obtained from the fit to the HST data. For objects of this colour, there is a negligible colour term between B and B(AB) passbands. For the purposes of this analysis we have therefore assumed $M_B(\mathrm{AB}) = M_B$ for the nuclear regions.

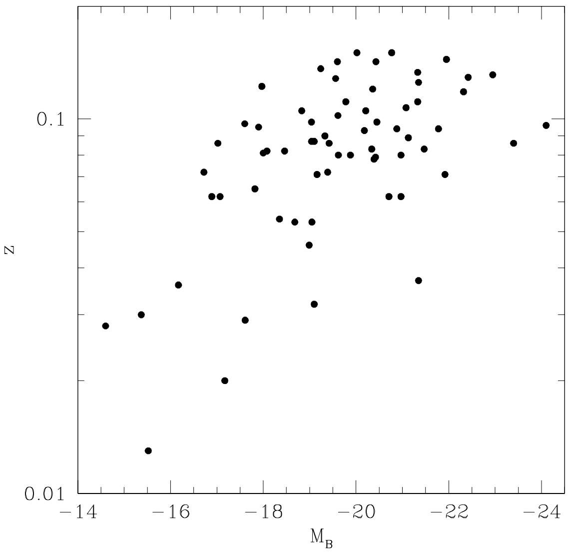

Figure 1. Nuclear absolute magnitude *v.* redshift for the 66 AGN with point source detections in SBL.

$L_{2500\mathrm{A}}$(nuc), listed in the SBL paper. L_{2500}Å(nuc) is based on the fitted nuclear M_B(nuc), assuming a power-law optical/UV spectrum of the form $f_\nu \propto \nu^{-0.5}$. Errors on the X-ray flux range from 5 per cent for the brightest X-ray sources to 25 per cent for the faintest X-ray sources (Gioia 1990). Although the X-ray luminosity for each source is expected to be dominated by the AGN, it is impossible to rule out some contribution from the host galaxy, particularly for the lowest luminosity sources.

The least-squares fit to the observed relationship between $L_{2\mathrm{keV}}$(nuc) and $L_{2500\mathrm{A}}$(nuc) plotted in Fig. 2 gives a relation of the form $L_{2\mathrm{keV}}(\mathrm{nuc}) \propto L_{2500\mathrm{A}}(\mathrm{nuc})^{0.82\pm0.08}$, consistent with other studies (e.g. Green et al. 1995).

2.2 The $1/V_a$ OLF estimate

Space densities were derived using the $1/V_a$ estimator (Avni & Bahcall 1980). The OLF was constructed from the summed contributions of n AGN using:

$$\Phi(M_B), z) = \sum_{i=1}^{n} \frac{1}{V_a^i}\, \delta(M_B^i - M_B)$$

V_a^i being the accessible co-moving volume of the i^{th} AGN. The estimate of V_a was based on $z_{\max}$ derived from the AGN's X-ray flux and EMSS flux limits, assuming an X-ray spectral index $\alpha_{\mathrm{X}} = 1$; $f_\nu \propto \nu^{-\alpha_{\mathrm{X}}}$. To construct an optical OLF, we binned the $1/V_a$ estimates according to their optical nuclear M_B magnitudes. We computed Poisson errors on the binned estimates of the OLF using $\sigma = \left(\sum \frac{1}{(V_a^i)^2}\right)^{0.5}$.

Not all 127 AGN with $z < 0.15$ in the EMSS were observed by SBL and so a straightforward normalising factor of 0.6 (76/127) was applied to the area coverage function when computing the accessible volume. KS tests confirmed that the redshift and flux distribution for the SBL sample

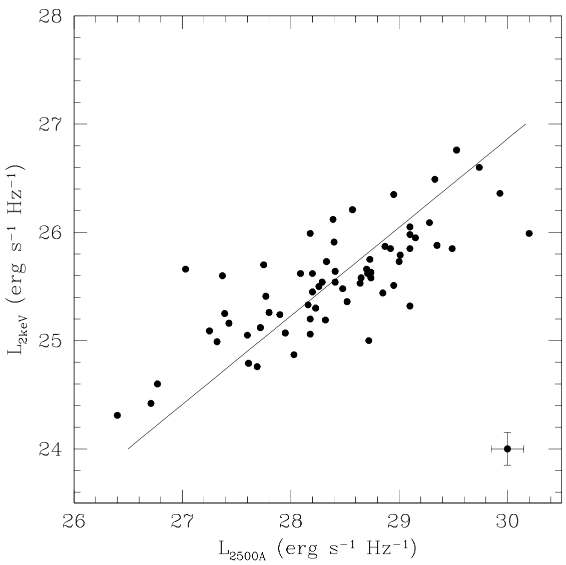

Figure 2. The correlation between nuclear UV and X-ray flux from the central component. The line is the slope of best fit calculated as 0.82 ± 0.08. Typical error on the flux estimates are shown in the lower right hand corner.

Table 1. Nuclear Optical Luminosity Function

M_B (nucleus)	Φ (Mpc^{-3} mag^{-1})	Objects
-24.00	$4.30 \pm 4.30 \times 10^{-8}$	1
-23.00	$3.98 \pm 3.98 \times 10^{-8}$	1
-22.00	$1.31 \pm 7.59 \times 10^{-8}$	3
-21.00	$5.61 \pm 1.91 \times 10^{-7}$	10
-20.00	$1.43 \pm 5.69 \times 10^{-7}$	14
-19.00	$1.90 \pm 5.63 \times 10^{-7}$	16
-18.00	$1.57 \pm 7.40 \times 10^{-7}$	7
-17.00	$3.42 \pm 1.63 \times 10^{-6}$	8
-16.00	$7.80 \pm 5.18 \times 10^{-7}$	3
-15.00	$3.38 \pm 2.54 \times 10^{-6}$	2
-14.00	$3.36 \pm 3.36 \times 10^{-6}$	1

is consistent with the sample being drawn at random from the $z < 0.15$ EMSS parent sample.

The OLF was calculated at 1-mag intervals for the full redshift range $z \leq 0.15$. We made no correction for evolution across the redshift bin. We also constructed separate OLFs for AGN in elliptical and spiral hosts to investigate any host-related trends.

3 RESULTS

The differential OLF calculated for an Einstein-de Sitter universe in which $H_0 = 50h_{50}$ km s^{-1} Mpc^{-1}, $\Omega_{\rm M} = 1$, $\Omega_\Lambda = 0$, is presented in Table 1 and plotted in Fig. 3, over plotted with data from K97 (their Table 5). As a comparison values using total galaxy luminosity (host + nucleus) are shown in Table 2 and plotted in Figure 5.

The K97 data comprises 27 objects extending out to a redshift of 0.3. Of these, eight were at redshifts greater than the $z = 0.15$ cut-off adopted in the SBL sample, all of which have $M_B < -24$, i.e. brighter than the most luminous AGN in the SBL sample.

Table 2. Total Optical Luminosity Function

M_B (host + AGN)	Φ (Mpc^{-3} mag^{-1})	Objects
-24.00	$4.30 \pm 4.30 \times 10^{-8}$	1
-23.00	$1.19 \pm 0.69 \times 10^{-8}$	3
-22.00	$9.92 \pm 2.55 \times 10^{-7}$	17
-21.00	$4.91 \pm 1.31 \times 10^{-6}$	28
-20.00	$6.98 \pm 3.69 \times 10^{-6}$	14
-19.00	$2.48 \pm 2.30 \times 10^{-6}$	2
-18.00	$1.09 \pm 1.09 \times 10^{-6}$	1

In Fig. 3 we have also plotted two predictions of the $z < 0.15$ OLF based on the luminosity evolution models of Boyle et al. (2000). These authors fit a variety of evolutionary models to a data set comprising over 6000 QSOs with $M_B < -23$ and $0.35 < z < 2.3$ selected from the 2dF QSO redshift survey (Boyle et al. 1999) and the Large Bright QSO survey (LBQS, Hewett et al. 1995). Boyle et al. (2000) found that luminosity evolution models provided acceptable fits to the data, with exponential evolution ($L^* \propto e^{k\tau}$) as a function of look back time (τ) favoured for a $q_0 = 0.05$ universe and as a general second order polynomial with redshift ($L^* \propto 10^{k_1 z + k_2 z^2}$) for $q_0 = 0.5$. The extrapolated $z < 0.15$ OLFs for the best-fitting 'exponential' and 'polynomial' models are shown as the short- and the long-dashed lines respectively in Fig. 3. The model OLFs have been plotted over the magnitude range consistent with the corresponding range (with respect to M_B^*) over which they were derived at $z > 0.35$. We obtained a reduced $\chi^2 = 1.0$ for the exponential model fit to the SBL data at $M_B < -19$, but were able to reject the extrapolation of the polynomial model at the 99 per cent confidence level.

4 DISCUSSION

There is good agreement both in slope and normalisation between our estimate of the OLF and the K97 OLF at $M_B < -20$. However, at fainter magnitudes the two estimates diverge. Our estimate of the OLF turns over to a much flatter slope whereas the K97 OLF continues to rise steeply. However, there are only three AGN in the K97 sample with $M_B > -20$, whereas the SBL sample contains 37 AGN at these fainter magnitudes. It is therefore most probable that the difference between the two data-sets (2σ) at these magnitudes is simply due to small number statistics in the K97 sample.

It is possible that the X-ray selection used to generate the SBL dataset is systematically biased against AGN with low optical luminosity. However, the correlation between $L_{\rm 2keV}$(nuc) and $L_{\rm 2500A}$(nuc) plotted in Fig. 2 demonstrates that there is no systematic trend for objects with lower optical luminosities to exhibit relatively weaker X-ray-to-optical flux ratios. Indeed, the derived relation $L_{\rm 2keV}({\rm nuc}) \propto L_{\rm 2500A}({\rm nuc})^{0.82\pm0.08}$ implies the reverse, i.e. that AGN with

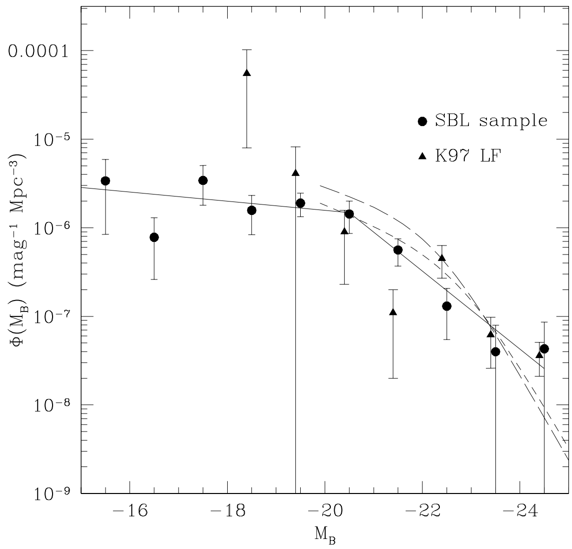

Figure 3. Binned OLF of the 66 AGN in the SBL survey (filled circles) compared with data from K97 (triangles). The solid line denotes the least squares fit to the data. Predicted $z < 0.15$ OLFs based on luminosity evolution models of Boyle et al. (2000) are also shown (short dashed line: 'exponential' model, long dashed line: 'polynomial' evolution, see text for details).

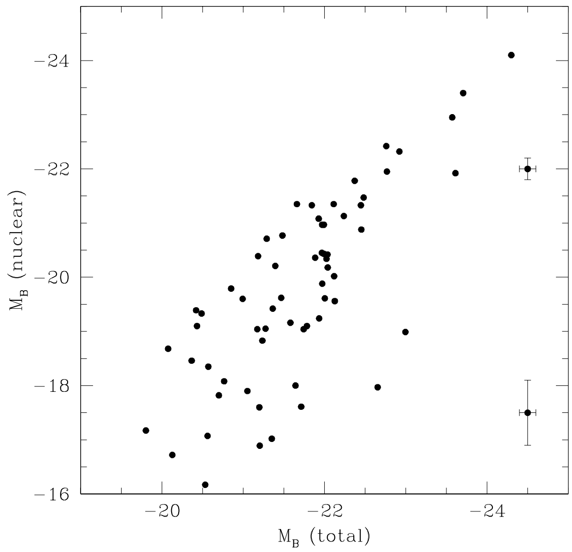

Figure 4. The relation between nuclear and total galaxy luminosity for the SBL dataset. At fainter magnitudes the distribution is very broad, with no clear correlation between nuclear and total luminosity. Typical errors for the nuclear component are indicated; errors are greater at fainter nuclear magnitudes.

lower optical luminosities have stronger X-ray-to-optical flux ratios.

In common with other groups (La Franca & Cristiani 1997, Goldschmidt & Miller 1998), K97 have used their determination of the low redshift OLF to claim that the slope of the bright end of the OLF ($\Phi(L)$) flattens significantly from $\Phi(L) \propto L^{-3.6}$ at $z > 0.6$ to $\Phi(L) \propto L^{-2.5}$ at $z < 0.3$. Such an observation would rule out pure luminosity evolution models, in which the shape of the OLF remains invariant with redshift. This is in marked constrast with our result that an extrapolation of the exponential form of a pure luminosity evolution model derived at $z > 0.35$ still provides an adequate fit to the $z < 0.15$ OLF.

To investigate the discrepancy between these results, we fitted our binned estimate of the $z < 0.15$ OLF with a two-power-law model of the form:

$$\Phi(L) \propto L^{\alpha} \qquad L > L^*$$

$$\Phi(L) \propto L^{\beta} \qquad L < L^*$$

Fixing a 'break' luminosity at $L^* \equiv M_B^* = -20.5$, we derived slopes of $\alpha = -2.1 \pm 0.3$ and $\beta = -1.1 \pm 0.1$ using a weighted least squares technique. This fit is over-plotted as the solid line on Fig. 3. This slope for α is indeed flatter than that derived at high redshift and is consistent with other estimates of the slope of the low redshift OLF, including the most recent determination of the bright end slope of the X-ray QSO LF ($\alpha = -2.6$) by Miyaji et al. (1998). However, the value of α derived in this crude fashion is strongly dependent the choice of M_B^*, and the inclusion of the two brightest bins that each contain a single object. By choosing a 'break' magnitude of $M_B = -21.5$, and restricting consideration of the data points in the OLF to those bins which contain more than one object, we can increase this value to $\alpha = -2.6 \pm 0.3$. This is, admittedly, a very crude analysis and more sophisticated fitting of a smooth two-power-law function similar to that used to fit the higher redshift OLF would yield a more accurate estimate of the statistical errors associated with fitting the OLF.

However, it is also likely that systematic errors play an equally important role in the determination of the local OLF. We attempted to estimate the sizes of such errors by first exploring the factor used to correct for the host galaxy luminosity.

In the SBL sample the host galaxy luminosity was explicitly removed using fits to the individual HST images. For the bulk of their sample (i.e. $0.07 < z < 0.3$, or $M_B < -22$) K97 relied on a two-step procedure using corrected CCD magnitudes measured in an aperture of diameter approximately equal to that of the seeing disk, hence replacing total magnitudes with small aperture magnitudes. Subsequently, a further correction factor for host galaxy luminosity was applied by adopting a template host galaxy of $M_B = -21$.

In Fig. 4 we have plotted nuclear luminosity against the total galaxy luminosity for the SBL sample. As also found by della Ceca et al. (1996), although the more powerful AGN reside in the more luminous hosts, the distribution of the ratio between nuclear and total luminosity is not constant; indeed the spread becomes very large at total absolute magnitudes fainter than $\sim M_B(\mathrm{nuc}) = -22.5$.

We re-computed our estimate of the $z < 0.15$ OLF based on the SBL dataset using total, instead of nuclear, absolute magnitudes. The resulting OLF is shown in Fig. 5, with the both the original fit derived for the OLF and the extrapolated model fits plotted as a comparison. We find that although the bright end of the OLF has steepened apprecia-

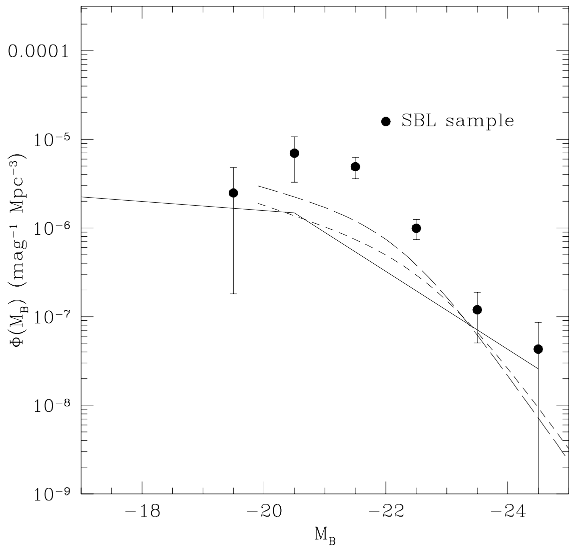

Figure 5. Binned LF of the 66 AGN in the SBL using total absolute magnitudes. Solid line: least-squares fit to original OLF; Short dashes line: OLF predicted by exponential evolution model; long dashes: OLF predicted by polynomial evolution model, see text for details.

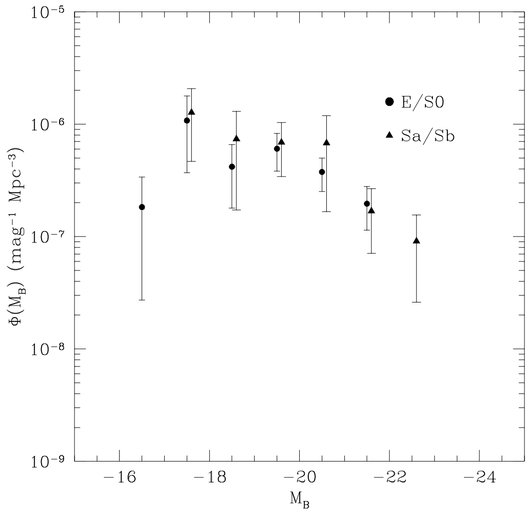

Figure 6. OLFs for the SBL sample split according to host galaxy. The points for the E/SO hosts are displaced to fainter magnitudes by 0.1 mag for clarity.

bly to $\alpha \sim -3$, both model fits are now clearly incompatible with the OLF computed in this fashion.

The treatment of galaxy luminosities can thus result in significant differences to the estimate of the OLF at zero redshift. Note also that the evolutionary models have been derived from high redshift OLFs uncorrected for host galaxy light. Although the assumption that the host galaxy light makes an increasingly small contribution to the total luminosity of QSOs at high redshift may well be correct, some spectacular counter-examples have already been discovered (Aretxaga et al. 1995, Brotherton et al. 1999).

We conclude that the large statisitical and systematic errors associated with the determination of the low redshift OLF and extrapolation of the OLF at higher redshifts make it difficult to rule out luminosity evolution models on the basis of shape of the low redshift OLF.

We also attempted to derive nuclear OLFs for AGN with bulge-dominant (E/S0) and disk-dominant (spiral) hosts. Following SBL, the distinction between the two broad classes and elliptical was made on the basis of the bulge-to-total light ratio, B/T, for the host galaxy. Galaxies with $B/T > 0.5$ were classified as E/S0 (44 in the sample), those with $B/T \leq 0.5$ as spiral (22 in the sample). The nuclear OLFs for different types of host galaxy is plotted in Fig. 6 (after re-normalising the E/SO LF to the same space density as the Sa/Sb LF). There are no significant differences between the two OLFs; confirmed by a KS test on the cumulative luminosity distributions for spiral and E/S0 hosts.

This result is consistent with observation by SBL that B/T for the host galaxy was independent of nuclear luminosity. In contrast, we note that McLure et al. (1999) found that the fraction of elliptical hosts increased significantly amongst the highest luminosity AGN. However, these observations are still based on relatively small datasets and the McLure et al. (1999) study predominantly samples a different luminosity regime ($M_B < -23$) to that under investigation in this analysis.

5 CONCLUSIONS

Results from a comprehensive, unbiased X-ray selected sample of AGN using the 0.1 arcsec resolving power of the HST, have enabled the first direct estimate of the nuclear OLF for AGN to be constructed.

The OLF derived illustrates a two power law form similar to that derived for QSOs at higher redshifts and as such is different to the largely featureless power-law OLF claimed for the low redshift AGN identified in the Hamburg/ESO QSO survey. However, any discrepancy only occurs at $M_B > -20$, where previous estimates of the OLF from the Hamburg/ESO survey are dominated by statistical errors arising from small number statistics.

The OLF is consistent with an extrapolation of the exponential pure luminosity evolution derived at $z > 0.35$ by Boyle et al. (2000), although the 'best-fit' slope for the bright-end slope of the OLF is flatter than predicted by such pure luminosity evolution models.

Given the large uncertainties associated with current estimates of the low redshift OLF (not least in the present analysis) and the extrapolation of evolutionary models to low redshift, it is almost certainly premature to rule out luminosity evolution on the basis of the current determinations of the low redshift OLF.

Further detailed imaging work on optically-selected samples of low-moderate redshift AGN/QSOs will clearly help resolve this issue. With the superior imaging capability of the new generation of ground-based telescopes (Keck, Gemini) we may look forward to such data being obtained in the near future.

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